ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY
COLLAGE OF ARCHITECTURE AND CIVIL ENGINEERING

EXPERIMENTAL INVESTIGATION OF BAMBOO AS A PARTIAL REPLACEMENT OF REBAR IN RC BEAMS

BY

SOFIA NESRU

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ADDISE ABABA, ETHIOPIA

ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

School of Graduate Studies

Collage of Architecture and Civil Engineering

Department of Civil Engineering

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Sofia Nesru (GSR/0078/05)

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Abstract

This study presented about flexural capacity of beams partially reinforced with bamboo as tension reinforcement and as a top reinforcement in compression zone. The bamboo sticks used as reinforcement on the beams were from Dilla Zone and tested against compression and tension; its strength found to be 46 & 120 Mpa respectively. Compared the experimental result with reinforced concrete beams and theoretically calculated values. Five beam samples were used for this purpose; singly reinforced and doubly reinforced beam. On singly reinforced beam, bamboo culms were used as a nominal reinforcement in compression zone and steel in tension zone. On doubly reinforced beam, 35% of tension reinforcement was replaced by 85% of bamboo to saw the effect of the replacement on load carrying capacity. As a result, for singly reinforced beam adding bamboo increased the load carrying capacity by 8% and for doubly reinforced beam, there was about 10% reduction on the flexural capacity compared with doubly reinforced RC beam but still safe for the design load.

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Acronym and Abbreviation

- ACI-American Concrete Institute
- ASTM-American Standard Test Method
- EBCS-Ethiopian Building Code of Standard
- FGM-Functionally Graded Material
- IS-Indian Standard
- ISO-International Organization of Standards
- MOE-Modulus of Elasticity

1. INTRODUCTION

1.1. Background of the study

In most countries, concrete is widely used as the foundation for the infrastructure. Concrete is used largely because it is economical, readily available and has suitable building properties such as its ability to support large compressive loads. However, the use of concrete is limited because it has low tensile strength. For this reason, it is reinforced, and one of the more popular reinforcing bars (rebar) is steel. Steel has a relatively high tensile strength, as high as 115 ksi (792 N/mm^2), complementing the low tensile strength of concrete.

Steel is available and affordable in most developed countries but unfortunately not all parts of the world. In many countries, none or very little steel reinforcement is used in construction, which is evident from the crumbling of buildings. Even today there exists a need for more economical and readily available substitute reinforcements for concrete. In some parts of the world many buildings are constructed only with concrete or mud-bricks. This is dangerous in case of seismic activity. These buildings have little hope of standing in the case of an earthquake. Steel reinforcement would be an ideal solution, but cost is a considerable problem. Scientists and engineers are constantly seeking for new materials for structural systems; the idea of using bamboo as possible reinforcement has gained popularity.

Bamboo is giant grass, not a tree. Bamboo culms are a cylindrical shell divided by solid transversal diaphragms at nodes and have some intriguing properties such as high strength in the direction parallel to the fibers, which run longitudinally along the length of the culm, and low strength in a direction perpendicular to the fibers. The density of fibers in cross-section of a bamboo shell varies with thickness as well as height. Fiber distribution is more uniform at the base than at the top or the middle. This is because bamboo is subjected to maximum bending stress due to wind at the top portion of the culm (Ghavami 2004).

Bamboo is a natural Functionally Graded Material (FGM). It is a composite with hierarchical structure. The strength of bamboo is greater than most of the timber products. The mechanical properties vary with height and age of the bamboo culm. Research findings indicate that the strength of bamboo increases with age. The optimum strength value occurs between 2.5 and 4 years. The strength decreases at a later age (Amanda and Untao 2001). The function of the nodes is to prevent buckling and they play a role of axial crack arresters. One major problem with bamboo is that it is a living organism which is subject to fungi and insect attacks. Bamboo is more prone to insect attack than other trees and grasses because of its high content of nutrients. In order to combat this problem, it becomes necessary to treat the bamboo to protect it from the environment.

One of the amazing aspects of bamboo is the way it interacts with the environment. It has been discovered that bamboo can prevent pollution by absorbing large amounts of nitrogen from waste water and reducing the amount of carbon dioxide in the air (Steinfield 2001). Some of the positive aspects such as a lightweight design, better flexibility, and toughness due to its thin walls with discretely distributed nodes and its great strength make it a good construction material. Bamboo is used as structural material for scaffolding at construction sites in India, China and other countries as it is a tough, flexible, light weight and low cost material. In nature when bamboo is covered with heavy snow, it will bend until it touches the ground without breaking. This implies that bamboo has greater flexibility than wood. “The energy necessary to produce 1 m^3 per unit stress projected in practice for materials commonly used in civil construction, such as steel or concrete, has been compared with bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo”. The tensile strength of bamboo is very high and can reach 54 ksi (370 N/mm^2). This makes bamboo an alternative to steel in tensile loading applications. This is due to the fact that the ratio of tensile strength to specific weight of bamboo is six times greater than that of steel (Amanda et al. 1997).

One of the properties that would make bamboo a good substitute to steel in reinforced concrete is its strength. The strength of bamboo is greater than most timber products which are advantageous, but it is approximately half the tensile strength of steel. Bamboo is easily accessible as it grows in almost every tropical and subtropical region; this lowers the cost of construction and increases the strength of the buildings that would otherwise be unreinforced. Bamboo is very light in weight compared to steel. Due to its low modulus of elasticity, bamboo can crack and deflect more than steel reinforcement under the same conditions. These aspects put bamboo on the list of viable construction materials. These properties, when combined, suggest that bamboo will make a fine addition to the current selection of materials, but it is necessary that people in general be made more familiar with its strengths and weaknesses.

Problems encountered with the commonly used construction material like steel are rise in cost; degradation of the non-renewable material, the pollution of the environment due to industrial process etc. are common in the globe. Scientists and engineers are constantly seeking for new methods and materials for structural systems such as recycling and reuse, sustainable production of products, or use of renewable resources like vegetable fibers including bamboo, jute and glass. Bamboo is one of the ecological materials for this purpose having many advantages. Some of these are;

- It reaches its full strength in just few months;
- It reaches its maximum strength in few years;
- Is renewable material
- Have simple production process
- Have high tensile strength along the fiber
- Have low weight
- Is corrosion resistance
- Low cost

Due to the above advantageous characteristics of bamboo, in the last few years, studies have been made on bamboo as structural material; full and partial reinforcement in concrete. The main obstacle for the application of bamboo as a reinforcement is the lack of sufficient information about its interaction with concrete, strength and durability. This thesis presents the results of experimental study carried and a concise summary about the strength of bamboo as a partial reinforcement and its interaction with concrete and steel.

1.2. Objective of the study

The general objective of this research is to study the potential use of bamboo as a partial reinforcement and investigate its flexural strength.

The following are the specific objectives that the study tried to achieve:

1. Determination of the physical and mechanical properties of Bamboo from Dila Zone
2. Flexural strength Investigation of Bamboo as a partial reinforcement in concrete beams.
3. Compare the experimental failure load with theoretical values.

1.3. Scope of the Study

Primary Source of Data includes reference materials like books, magazines, standards and websites.

To meet the above-mentioned objectives, bamboo samples from Dila zone were collected for the investigation. Experimental program were made to find out the mechanical properties of Y.Alpino bamboo. Then, experimental program on Tensile test for different splits and flexural test for different percentage were performed.

Samples tested for the tensile, compression and flexural tests were prepared in the following manner. The flexural strength by varying the place and percentage of bamboo as top and bottom reinforcement were also conducted. Moreover failure loads were done using hand calculation for comparison purpose. All bamboos are treated with hot bitumen asphalt coat for bonding purpose.

In the preparation of samples and conducting tests the guideline in IS ACI and ASTM standards were followed.

1.4. Limitation of the study

The following things were not included on this study

- Flexural behavior of steel bamboo reinforced concrete beams with bamboo stirrups
- Study about bond length and development length
- Treatment method of bamboo
- Long term effect of bamboo as reinforcement
- Flexural test of steel bamboo reinforced beam intended to fail in shear
- Investigation of steel bamboo reinforced beams with different support system
- Ductility behavior of bamboo and steel in beams.

1.5. Organization of the Thesis

This work is organized in six chapters. The first is devoted to brief description of the thesis background, objectives, scope, and the methodology. The second chapter presents literature review on bamboo characteristics, historical development as reinforcement and bond strength, storage, harvesting and diversity of bamboo in Ethiopia. The third chapter deals with the experimental program made in the sample preparation and test set up for mechanical properties, tensile and flexural tests. The fourth chapter addresses laboratory test results. The fifth chapter deals with analysis and discussion on mechanical properties and flexural test results. The last chapter devoted to draw conclusions and recommendation.

2. REVIEW OF THE RELATED LITRATURE

2.1 Introduction

This chapter outlines; the theoretical and empirical literature on the potential uses of bamboo as a partial reinforcement and investigate its flexural strength. The aim of this chapter is to review and study the existing literature and theory that related to the study. The purpose is to assemble theoretical literature to make strong study together with experimental tests in this study. This chapter begins with the concept bamboo and its property, diversity of bamboo in Ethiopia, bamboo harvesting and seasoning, mechanical properties of natural bamboo, structural applications of bamboo, bamboo for civil construction as reinforcement and bond strength of bamboo.

2.2. Overview of Bamboo Characteristics and Its Property

The bamboos are evergreen perennial flowering plants in the subfamily Bambusoideae of the grass family Poaceae. In bamboo, as in other grasses, the intermodal regions of the stem are usually hollow and the vascular bundles in the cross section are scattered through the stem instead of in cylinderal arrangement**.** It is estimated that 60–90 generae of bamboo exist, encompass approximately 1100–1500 species and there are also about 600 different botanical species of bamboo in the world. Bamboo mainly grows in tropical and sub-tropical regions of Asia, Latin America and Africa. The use of agricultural by-products, which are environmentally benign, such as rice husk, coconut fibers, sisal and bamboo minimizing energy consumption, conserving non-renewable natural resources, reducing pollution and maintaining a healthy environment. Bamboo is one of the ecological materials which absorb carbon dioxide and release 35% of more oxygen than any other hard woods bamboogrove.com (why bamboo save the planet).

Bamboo is a member of the larger grass family and there are hundreds of species worldwide. Species range from small diameter 'reed like' bamboo to large diameter woody bamboo that is often used in construction. A functionally graded, natural fiber-reinforced material, bamboo has evolved in nature to efficiently resist environmental loads such as wind and gravity. Bamboo has been shown to have mechanical properties comparable to those of conventional building resources. Additionally, its availability worldwide gives it great potential as a building material. Bamboo plantations of various sizes can also benefit from the advantageous growing properties of bamboo and the multitude of uses for the harvest. However, as an organic material, bamboo must be seasoned and preserved properly for intended uses, especially for exposed structures.

2.2.1 Bamboo Taxonomy and Classification

Bamboo is a member the grass family *Poaceae* or *Gramineae*. The family classification is then divided into sub-families, tribes, sub-tribes, genera, and species (Chapman and Peat 1992). The bamboo sub-family, *Bambusoideae*, is associated with the woody culm bamboo and is the "most primitive subfamily in terms of flower structure" (Chapman and Peat 1992). *Bambusoideae* is composed of 13 or 15 tribes based on the two widely used grass classifications from 1992, Clayton and Renvoize or Watson and Dallwitz respectively (Chapman 1996). The largest tribe, *Bambuseae* is the woody bamboo tribe and is divided into various sub-tribes. The sub-tribes are then divided into multiple genera such as *Arundinaria*, *Bambusa*, *Chusquea*, *Dendrocalamus*, *Gigantochloa*, *Guadua*, *Melocanna*, *Merostachys*, *Nastus*, *Phyllostachys*, *Rhipidocladum*, and *Schizostachyum* (Chapman and Peat 1992, Clark and Pohl 1996). An early 1966 estimate by McClure classified bamboo into 63 genera and approximately 700 species (Liese 1987) but this number has grown to between 1000 and 1500 species (Grewal 2009; Laroque 2007). Common species of large diameter bamboo used in construction include *Phyllostachys heterocycla pubescens* (Moso), *Bambusa Stenostachya* (Tre Gai), *Guadua angustifolia* (Guadua), and *Dendrocalamus Giganteus* (Dendrocalamus). The experimental portion of this work includes specimens of Moso, Tre Gai and Dendrocalamus.

2.2.2 Bamboo Anatomy, Structure, and Growth

The two main anatomical features of the bamboo plant are (a) the visible culms or stalks of bamboo which are ultimately used as the raw material for construction and (b) the underground rhizome system. Bamboo grows and matures rapidly yet only flowers once in its lifetime. Most new culm production is achieved through the expansion of the rhizome system.

2.2.2.1 The Bamboo Culm

For most woody species, the structure of bamboo is composed of culms with solid transverse diaphragms or nodes separating hollow inter-nodal regions along its height. Generally, depending on species, the length of internodes between diaphragms increases along most of the culm height, decreasing as it reaches the very top of the culm (Amada et al. 1996). The circular cross section is composed of unidirectional cellulosic fibers oriented parallel to the culm's longitudinal axis embedded in a lignin matrix. Bamboo is a functionally graded material that has evolved to resist its primary loading in nature: its own self weight and the lateral loading effects of wind. The density of fibers increases from the culm's inner wall to the outer wall. In some species such as Tre Gai, the wall thickness of the bamboo culm will be largest at the base of the culm and decrease with height up the culm, also demonstrating a naturally efficient use of material to resist overturning due to wind while reducing gravity loads. Finally, the thin outside layer of the culm wall (approximately 0.25 mm thick) is dense and contains silica, which serves as good protection for the plant but can dull tools when bamboo is used in construction (Janssen 2000).

While alive, the culm is both the structural support of the bamboo and the conduit for water and sap transportation. The culm is composed of approximately 40% cellulose fibers, 10% vessels and 50% parenchyma tissue (Janssen 2000). The parenchyma tissue matrix in which fibers and vessels are embedded begins to harden or lignify over time as the culm grows. The fibers which provide the culm's strength are grouped around vessels for water and sap transport in vascular bundles. The conducting vessels are 'capped' by the bamboo fibers (darker cells) and surrounded by parenchyma. The vascular bundles are large and less densely packed near the interior wall while near the outer wall they become smaller as the vessels decrease in size and become more densely packed. The vascular bundles are also oriented such that they are 'strongest' in the radial direction of the culm. The size and quantity of vessels decrease with the height of the culm (used for nutrient transport, their volume may be reduced with increased culm height) and are replaced with bamboo fibers. This addition of fibers compensates for the loss in strength and stiffness due to reductions in diameter and wall thickness near the top of the culm (Janssen 2000). Grosser and Liese (1971) outlined four basic vascular bundle types varying in shape and size and studied how these are distributed through the cross section and vertically in various bamboo species. They used the four basic bundle types and their combinations, along with the radial order of vascular bundles in the cross section to classify species of Asian bamboo from various genera.

2.2.2.2 The Rhizomes

While the culm is the primary product used for construction and other applications, the underground rhizome system is equally important as it is responsible for the rapid growth and production of bamboo culm (sometimes referred to as the bamboo factory). Rhizomes are not a root but rather an underground stem having nodes and internodes that grows laterally (Clark and

Pohl 1996). There are two basic forms of rhizome systems: leptomorphs and pachymorphs. A leptomorph rhizome system has larger internodes that grow or ‘run’ out laterally. New culms grow up and out from lateral buds at each internode perpendicular to this lateral underground stem. These species, known as running bamboo, can spread widely and are potentially invasive. The genus Phyllostachys is an example of a running bamboo (Clark and Pohl 1996). A pachymorph rhizome system has short and thick rhizomes that grow out and turn upwards to form new vertical culms. This causes the culms of a plant to be densely packed or ‘clumped’ together. These species are referred to as clumping bamboo. Some species have been found to have characteristics of both forms and are classified as amphimorph rhizomes (Clark and Pohl 1996).

The extensive network of bamboo rhizomes effectively binds up the soil to a depth of approximately 300 mm (Chapman and Peat 1992). This makes removal of bamboo difficult although planters are investigating ways to use the rhizome material for products. The rhizome system also has potential for providing soil stabilization. Janssen (2000) writes that there have been cases of bamboo preventing riverbank erosions and therefore protecting villages. However, while the rhizomes are effective in binding up the soil, the shallowness and density of the underground system also introduces a potential weak plane between the bound shallow soil and the soil beneath the rhizomes. In the northeast hill region of India, for example, stands of clumping bamboo are believed to be the cause of slope failures during the rainy season as the heavy clumps and attendant soil slips along the weak shallow plane beneath the rhizomes.

2.3. Diversity of Bamboo in Ethiopia

Different bamboo species are available here in Ethiopia. Ethiopia has Africa’s biggest Bamboo Resources and this wooden grass can be harvested in sustainable cycles on 30%-40% of the mature culms every two years. The total resource base of Ethiopia is confined to two indigenous bamboo species out of more than 1500 species of bamboo in the world and 43 species in Africa. The highland bamboo (*Yushania alpina),* 8cm diameter and 17m height covers 15% and the monotypic genus lowland bamboo(*Oxythenantera abyssinica),* with solid culms at maturing age, 5cm diameter and 7m high covers 85% .The location of the bamboo rich sources in Ethiopia are Assosa, Injibara, Gimbi, Ambo, Gurage, Bale, Masha, Chencha and Hagere-Selam are rich in bamboo sources. Even though, there are large source of bamboo in Assosa it is lowland type of bamboo which has solid culm at maturating age. Due to its solid culm behavior at maturating age it is not preferable to use bamboo splits as reinforcement. This is because as wall thickness increase the internal soft part thickness will increase. Consequently the durability, compactness and the average tensile strength will be decreased. Therefore, due to its abundance, thin wall thickness nature and accessibility, bamboo species from the highlands of Gurage called Dila or Hagere-Selam was selected for this investigation.

Figure 2.1 Diversity of Bamboo in Ethiopia (From ECBP-Documentation, Workshop Presentation)

2.4. Bamboo Harvesting and Seasoning

Once a bamboo culm has matured 3 to 5 years, it is ready for harvest. One environmental benefit of bamboo harvesting is that there is no clear cutting of large areas. Rather the mature culms are selectively cut while remaining culms continue to grow and mature. This keeps the environment and habitat of the bamboo forest or plantation intact (Janssen 2000) and ensures a continuous supply of new culms, maturing culms, and culms ready for harvest. Harvesting can be done manually with hand cutting tools or using mechanical equipment depending on the scale and location of the plantation. At Bambuparque, a small chainsaw is used to harvest culms of *P. aurea* and culms are cut to standard 3 meter lengths. Culms are harvested at 5 years of age from May till September (winter) when the bamboo has the least water and starch and therefore greatest durability against insects and fungi. Culms are cut at a node to prevent water infiltration and rot in the remaining stump. Sr. Inglês also only harvests between the third quarter and new phases of the moon; a practice believed to reduce starch content yet no correlation between durability and moon phases is established (Janssen 2000). Any harvested culms of inferior quality are used as firewood. After treatment of the bamboo, the culms are stacked in an open shed to air dry.

Air drying and kiln drying are the common methods of seasoning bamboo. Air drying typically takes 6 to 12 weeks while kiln drying in thermally insulated chambers takes 2 to 3 weeks (Laroque 2007). For air drying, the primary concern is that culms are protected from the elements (i.e. rain) with a roof or canopy and have the ability to dry quickly if exposed to moisture. Culms should also be laid horizontally with sufficient room to provide air movement and be free from soil (Janssen 2000). Bamboo often needs a longer drying period than conventional timber due to its higher moisture content (Liese 1987). With this initial high moisture content, bamboo experiences a large amount of shrinkage during seasoning; this leads to the issue of cracking and even collapse. The bamboo tissue primarily shrinks in the radial direction of the cross section (Liese 1987) with thick walled bamboo being more susceptible to cracking than a thin walled species.

2.4.1. Bamboo Treatment and Preservation

Untreated, the durability of bamboo varies based on the species, age, and conservation actions taken (Ghavami 2008). In the open and in contact with soil, bamboo is estimated to last 1 to 3 years; 4 to 6 years if under cover and free from soil contact (Janssen 2000, Jayanetti and Follett 2008). Only under very good storage/use conditions is untreated bamboo estimated to last 10 to 15 years. The main culprits in bamboo degradation are water ingress, fungal attack, and infestation by insects and rodents. Fungi and insects are attracted to the starch content in the culm and animals can nest in hollow internodes. These issues are combated by the proper design and detailing of structures (Janssen 2000, Jayanetti and Follett 2008). Best practices include roof overhangs, good air circulation, drainage, the plugging of open culm ends, and ensuring no contact between a bamboo structure and soil (termite prevention). Janssen (2000) states bamboo 36 has less natural durability than most woods due to the absence of certain chemicals yet Li et al. (2007) states that extractive contents analogous to both trees and bamboo may help with natural decay resistance. Ultimately, treatment processes can greatly extend the life of bamboo culms and their corresponding structures. Janssen (2000) writes that, while the price of bamboo increases approximately 30% with preservation treatment, the service life can be increased to 15 years in exterior exposure and to 25 years under cover. Preservatives range from oil based, oil soluble, water soluble, tar oil and boron-based chemicals, all of which are relatively safe options (Jayanetti and Follett 2008). Boron based chemicals such as borax and boric acid are also considered effective and inexpensive. The high silica content of the outer layer of bamboo, while providing good resistance to water and insects, also prevents infiltration of preservative. The inner layer of bamboo is also impermeable (Janssen 2000). Infiltration of preservative can only occur through the ends of the culm and the conducting vessels. These vessels close within 24 hours of harvest and therefore treatment process must occur shortly after harvest and before seasoning (Janssen 2000). Preservation methods range in technique and complexity. Traditional methods include curing, smoking, soaking, and lime-washing of bamboo. Traditional soaking involves submerging culms in water for 6 weeks during which water soluble starch is removed from the culm. The dip diffusion method involves immersing bamboo in a chemical solution bath. In the rural village of Camburi, Brazil, culms are soaked for 2 weeks in a stone pool filled with a solution of water and disodium octaborate tetrahydride (Octabor). Small holes are drilled into each internode for the solution to penetrate inside the culm. The vertical soak diffusion method involves hanging bamboo culms, which have all nodes punctured except the final node, vertically and pouring a chemical solution onto them (Adhikary 2008, Janssen 2000). Fire treating of bamboo culms is another simple method that works for species such as *P. aurea*. At the plantation in Bananal, Brazil, the culms are washed thoroughly and then heated with a simple hand torch and propane tank. The culm begins to sweat pyroligneous acid which is diluted with a kerosene soaked rag and spread over the culm surface. This acts as a protective varnish for the bamboo culm. The process takes approximately 15 minutes per 3 m long culm (32 culms per 8 hour day); one tank of propane, estimated to be a standard 9.1 kg (20 lb) tank, can treat approximately 200 culms. Another common method for treating bamboo is the modified Boucherie method. This method passes a pressurized chemical solution through the conducting vessels of the culm to replace the existing sap (Adhikary 2008).

A pressurized tank holds the chemical solution such as a boron compound. An airtight rubber nozzle is then attached to one end of the bamboo culm. The chemical compound is forced through the culm to replace the natural sap which seeps out the opposite open end of the culm. Once all the sap has been removed and replaced with preservative, the culm is stored for drying and seasoning. This system can be set up locally in rural communities and has been shown to treat 1200 culms per month (Adhikary 2008). A fast and effective process, the system only needs simple instruction to operate. Additionally, a range of preservative solutions can be used including cow urine or neem oil. The Boucherie method only requires that the bamboo be treated immediately after cutting and a sufficient number of culms are available to be cost effective.

2.5. Mechanical Properties of Natural Bamboo

Bamboo is a promising engineered construction material because it has mechanical properties comparable to those of conventional building materials. While specifics of the mechanical properties of bamboo are discussed in detail in the pursuing chapters, these properties are highly correlated to the percentage and distribution of bamboo fibers within the culm cross section. Mechanical properties are influenced greatly by the specific gravity, which depends on fiber content, fiber diameter, and cell wall thickness (Janssen 2000). The density of 39 most bamboos is 700 – 800 kg/m^3 but depends on species, growing conditions, and even the position in the culm. The fibers are approximately 60 – 70% by weight of the culm tissue. The density or volume fraction of fibers is approximately 60% at the exterior face of the culm wall and 10-15% at the interior face. Density also increases along the height of a culm (Janssen 2000, Amada et al. 1996). The fiber length is longest in the middle of the culm wall section and is shorter at both the inner and outer wall faces. The shortest fibers are always at nodes. Janssen (2000) states the longitudinal modulus of elasticity is correlated to the number of vascular bundles per mm2, while the elastic bending stress (modulus of rupture) relates to fiber length.

2.5.1. Modulus of Elasticity

For the modulus of elasticity, research has focused on developing equations to account for the number and gradation of the bamboo fibers which effect stiffness. Janssen (2000) states that the functional gradation of fibers in the cross section increases stiffness by 10% as compared to an even distribution of the same volume of fibers. Using an elastic modulus of 70,000 N/mm2 for cellulose and assuming a bamboo fiber is 50% cellulose, the apparent or effective modulus is E=35,000 N/mm2. This number is then be multiplied by the percentage of fibers in the outer and inner layers of the culm (Janssen 2000). Another technique is to determine the volume fraction of the bamboo fibers across the wall thickness. This volume fraction is then used with the rule of mixtures to determine the modulus of elasticity across the wall thickness (Amada et al. 1996, Ghavami et al. 2003, Ghavami 2008, Li and Shen 2011).

2.5.2. Flexural Strength

Janssen (2000) estimated the bending stress at failure for air-dry bamboo as 0.14 times the density in kg/m3. However, in typical bending tests, the mode of failure is not fracture of the 40 fibers but rather longitudinal splitting of the material due to fracture of the weaker lignin bonding the fibers together. This is due to the shear in the section (i.e.: *VQ/It* shear) overcoming the capacity of the relatively weak lignin. Janssen (2000) gives a critical value of transversal strain as 0.0013 for establishing the bending capacity of bamboo. Using a Poisson's coefficient of 0.3 and a modulus of E = 17000 N/mm2, a critical longitudinal strain of 0.00373 and an ultimate bending stress of 62 N/mm^2 are estimated, "a typical outcome" in tests (Janssen 2000).

2.5.3. Compression Strength

The compression strength of full-culm bamboo has been studied by multiple authors. As with bending strength, Janssen (2000) estimated the ultimate compressive stress of air-dry bamboo as 0.094 times the density in kg/m3. During a typical compression test, the specimen often develops vertical cracks and bulges laterally (like a wooden barrel). The friction caused by contact with the loading plates holds the specimen together and can be a factor in the reported compressive strength value. Therefore, Arce-Villalobos (1993) called for the use of friction-free loading plates during testing. Arce-Villalobos (1993) also states that lignin plays a large role in bamboo failure under compression as tangential expansive forces lead to critical tangential strains.

2.5.4. Tensile Strength

The tensile strength of bamboo has been shown to be quite high and vary widely between species. Bamboo has been cited as having tensile strength similar to mild steel in some cases (Laroque 2007). As with Young's modulus, tensile strength is influenced primarily by the bamboo fiber volume ratio (Janssen 1981). Amada et al. (1996, 1997) studied tensile specimens from two year old *Phyllostachys edulis Riv.* (Mousou bamboo) and found that the tensile strength 41 of the bamboo (140-230 MPa) was greater than that of common woods such as fir, pine, and spruce (~30-50 MPa). Using the rule of mixtures, the tensile strength of the lignin matrix was estimated to be 50 MPa and that of a vascular bundle to be 610 MPa (12 times larger). The tensile modulus of elasticity was 2 GPa and 46 GPa for the matrix and bundle respectively

(Amada et al. 1996, 1997). Due to their entangled fibers, bamboo nodes show more isotropic behavior and lower tensile strength (Amada et al. 1997). While bamboo has good tensile strength in the direction of the fibers, a more critical value of bamboo strength is the tensile strength perpendicular to the unidirectional fibers. When tension is applied in the transverse direction, only the lignin matrix acts to resist the applied stress. This leads to splitting and cracking failures. Studies have shown that bamboo fails at a specific transverse strain of approximately 0.001 and that this value should be used as a limiting criterion for design (Arce-Villalobos 1993). This value can also be correlated to performance in the longitudinal direction since bamboo has a stable Poisson's ratio of approximately 0.3 (Janssen 1981).

2.5.5. Shear Strength

As described above, the strength of the lignin matrix is often the limiting factor for strength. Therefore, longitudinal splitting and shear strength are important characteristics for bamboo used in construction. In comparison with timber, the hollow cross section of the culm has less area to resist shear than timber although bamboo does not have defects such as knots. However, since bamboo fibers are only oriented in the longitudinal direction, there are two asymmetric shear planes in bamboo: a shear plane across the cross section of the culm and a shear plane parallel to the fibers. For a bamboo culm in flexure, Janssen (2000) estimates the critical shear stress at the neutral axis as 2.2 N/mm^2.

2.5.6. Commentary on Bamboo Material Properties

As can be seen in previous sections, a great deal of what is known of the material properties of bamboo consist of 'rules of thumb' or gross generalizations. Single values of limiting strain and properties estimated as a function of density value known to vary considerably based on many parameters are not conducive to engineering standardization, particularly for the many bamboo species viable for construction applications. This work, along with those of Mitch (2009, 2010) and Sharma (2010), attempts to provide a framework for a better understanding and ultimately standardization of bamboo material properties and tests to determine them.

2.6. Structural Applications of Bamboo

The applications of bamboo material in construction are numerous. While many think of bamboo in the form of the proverbial bamboo hut, the material is used in a range of temporary and permanent structures in both natural and engineered forms. The following section focuses primarily on bamboo structures constructed with full-culm bamboo. The use of full-culm bamboo is often limited by the jointing techniques used or available and therefore a discussion of this topic is also provided. Another key aspect of the potential of bamboo structures is their ability to provide hazard mitigation and performance during extreme loading such as seismic events. Finally, mention is given to engineered bamboo products as well as the use of bamboo with other materials such as concrete and timber in the form of composites.

2.6.1. Bamboo Structures

The primary use of bamboo is in construction and its utilization encompasses a wide range of applications and forms, both temporary and permanent. For the current discussion, attention is focused on the use of natural full-culm bamboo rather than engineered bamboo products. Bamboo scaffolding continues to be used throughout Southeast Asia and has traditionally been used in countries like China, India, and Thailand (Janssen 2000). One of the advantages of bamboo scaffolding is its capacity and reliability in resisting hurricane force winds (Janssen 2000, Chapman 1996). Jayanetti and Follett (2008) cite non-standardized jointing techniques and lack of durability as issues hindering wider acceptance of bamboo scaffolding.

In most cases, bamboo is used for the construction of houses and community buildings like the showcases a bamboo schoolhouse in the village of Mungpoo, India. Composed of a bamboo frame, simple multiple-culm bolted connections are used for connections to framing members. Four-culm columns are founded on concrete plinths having reinforcing bar extending and grouted into each culm (Mitch 2010).

Panels of woven bamboo strips are then used for the infill walls. The school is committed to sustainability and plans to construct all of its buildings using locally sourced bamboo. The bamboo community center in the rural coastal village of Camburi in São Paulo State, Brazil. The center was constructed by the Belgium organization Bamboostic with the goal of promoting construction in the village using local stocks of bamboo (Choi et al. 2011, Ghavami 2008). Culms of *Guadua angustifolia* (Guadua) and *Phyllostachys pubescens* (Moso) were used in the construction as well as compacted earth bricks and terracotta roof tiles. Culms were treated on site in a stone.

2.7. Bamboo for Civil Construction

Bamboo is one of the most important natures substitute for the endangered rainforest hard woods. it is a quick growing, versatile, non-timber forest product whose rate of biomass generation is unsurpassed by any other plants. The strength of the culms, their straightness, smoothness, lightness combined with hardness and greater hollowness; the facility and regularity with which they can be split; the different sizes, various lengths and thickness of their joints make them suitable for numerous end products**.**The bamboo culm, in general, is a cylindrical shell, which is divided by transversal diaphragms at the nodes. Bamboo shells are orthotropic materials with high strength in the direction parallel to the fibers and low strength perpendicular to the fibers. The thickness and strength of bamboo, however, decreases from the base to the top of the bamboo shell.

The density of the fibers in the cross-section of a bamboo shell varies along its thickness. On the outer skin of a bamboo shell the fibers are concentrated and more resistant to environmental degradation. This presents a functionally gradient material, grew according to the state of stress distribution in its natural environment. In view of the hollowness and the fibers in longitudinal direction, bamboo has a very efficient natural structural design and less material mass is needed than materials with a massive section, such as timber. In terms of load-bearing mass, as with all tubular elements, bamboo functions as an I-shaped cross-section, in each direction it is loaded, whereas other cross-sections are most efficient in one or two directions.

The energy necessary to produce 1 m3 per unit stress projected in practice for materials commonly used in civil construction, such as steel or concrete, has been compared with that of bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo. Different researchers conduct tests on the mechanical properties for different species of bamboo as a function of age moisture content and density. Research findings indicate that, the strength of bamboo increases around the initial then decreases on later age. The optimum strength value occurs between 2.5 to 4 years. Moreover, the strength decreases from bottom to top. Many researchers describe that bamboo has a tensile strength greater than 150MPa and reaches up to 300MPa. The ratio of tensile strength to specific weight of bamboo is six times greater than that of steel.

The structural advantage, over other engineering materials is studied in terms of modulus of elasticity, E, and density, ρ, using the material selection method developed at Cambridge

University. From this research based on the above criteria it has been shown that bamboo has a better performance, whereas, steel, concrete and aluminum have worse performance.

2.7.1. Bamboo as Reinforcement

No other plant material can rival the utility of bamboo. Even in the early years, bamboo had been used in many ways, not to mention the traditional use of bamboo in the daily life of the early people especially in Asia. Thomase Edison used bamboo as rebar for the reinforcement of swimming pool**.** Now days research about Bamboo reinforcement have been studied for several years among which include the most extensive and organized publication made by US Naval Civil Engineering Laboratory in 1966. In this paper preparation, mix design, placement anchorage and design principle of bamboo reinforced concrete were discussed in detail. This study suggests splits of bamboo approximately ¾ inch (19mm) wide to perform better bond strength. It is recommended, according to the paper, the same concrete mix design as for steel but the concrete slump should be as low as workability will allow minimizing swelling of bamboo due to excess water. It also suggests a splicing in any member should be at least overlapped 25 inches (635mm).

Ghavami K. (2004) has studied the behavior of bamboo in the reinforcement of beams. The bamboo strips used for this research were 30cm wide rectangular sections which were coated with thin layer of impermeable product and roughed with sand. By varying the percentage of bamboo from 0.75% to 5% flexural tests were performed. The test result had demonstrated that the ultimate applied load increased by more than 400% as compared with concrete beams without reinforcement, for a 3% bamboo reinforcement. Fikremariam M. (2010) has studied the flexural and bond strength of Gumero Bamboo on concrete beams. It was found the load carrying capacity of bamboo reinforced sections were 45% with that of RC beams.

On bamboo forums Meckes summaries the results obtained from the tests of bamboo reinforced concrete beams by Glenn H. E. It was concluded that load required to cause the failure of concrete beams reinforced with bamboo was from four to five times greater than that required for concrete members having equal dimensions with no reinforcement.

Moreover, it was also confirmed that concrete members reinforced with seasoned bamboo treated with a brush coat of asphalt emulsion developed greater load capacities than did equal sections in which the bamboo reinforcement was seasoned untreated or unseasoned bamboo. Janssen (1995) discussed the practicability of bamboo as reinforcement and recommends a design guide line for bamboo reinforced concrete beams. In concrete, the common tensile stress in steel is 160N/mm2, and in bamboo 20 N/mm2, a ratio of 8:1 and the mass per unit volume is 7850kg/m3 and 500 kg/m3 respectively, a ratio of 16:1. Consequently, bamboo will be cheaper because the price by weight of bamboo will be less than half that of steel. It strongly recommends melted bitumen for both to increase bond and protect bamboo from alkaline attack. With this precaution, a concrete beam with 4% bamboo as a reinforcement and 20N/mm2 tensile stress in bamboo, can be designed with a formulae M

$= 0.75h*0.04*bh*20 = 0.6bh^2$ [where M is bending moment, 0.75h is distance between compression and tensile force in a beam, 0.04 is percentage of reinforcement, b width and h is height of the beam.

Saucier K.L and Smith E.F has conducted experimental test on two series of bamboo reinforced pre-cast concrete beams. Series I, designed to study the behavior of optimally reinforced pre-cast concrete beams and series II designed to study the behavior of maximally reinforced pre-cast concrete beams. The test results showed that series II beams sustained approximately twice the load that was sustained by series I beams at a corresponding deflection. From this, it was concluded that the maximum amount of bamboo reinforcement that can be reasonably placed in the beam was used, to obtain a maximum load carrying capacity of bamboo reinforced concrete flexural members.

2.7.2. Bond Strength of Bamboo

When fresh concrete poured, its water moistens the bamboo. Then during the next month the concrete will harden and loss water so it will again dry out. This drying process can result in shrinkage of bamboo with more than the shrinkage of concrete. The differecial shrinkage breaks down the bond between concrete interface and bamboo. But, in case of steel bar the dimensions will remain constant while the concrete shrinks. Consequently this problem will not happen in steel reinforcement. To minimize the above problem many researchers have been made on bond strength with different treatment and suggest techniques that improve the durability as well as the bond strength of bamboo. Here, few outcomes of the researches are discussed in detail.

Ghavami K. (2004) discussed the factors that affect the bond strength between the bamboo and the concrete. These governing factors are adhesive properties of the cement matrix, the diameter of bamboo, concrete spacing, the compression friction forces appearing on the surface of the reinforcing bar due to shrinkage of the concrete and the shear resistance of concrete due to surface form and roughness of the reinforcing bar**.** The researcher spell out that by applying Sikadur 32-Gel on the surface of reinforcing bamboo segments increases the bond strength by 5.29 times compared to that of untreated segment. Other researcher called Janssen discusses four techniques that minimize shrinkage and increase bond strength of bamboo. The methods are;

1. Melting bitumen and applying it to the bamboo strips uniformly with a brush to form thin coats while still hot, the bamboo is covered with coarse sand for 24hours. The bitumen has proved an effective moisture barrier and the sand makes rough surface thus improving the bond.
2. Melting bitumen, as above, but 25mm diameter nails are driven into the bamboo Strips 75mm apart, so that they protrude on either side of the strips. This nails will maintain the bond.
3. Outer half of the bamboo possesses better tensile strength, better young's modulus and less shrinkage than the inner part. In order that uses of only the outer half of the bamboo as reinforcement is recommended.
4. Bitumen coat, but the bond is provided by roughly 3mm diameter coconut fiber ropes wound around the strips at a 100mm pitch along their length. The rope is also dipped in hot bitumen before being wound around the bamboo strips.

US Patent 4137685 - Sulfur-coated bamboo reinforcement member for concrete articles provides a moisture resistant, non-swelling bamboo reinforcement member for concrete containing a roughened bamboo surface and a substantially continuous coating of crystallized sulfur contacting and adhering to the cortex to prevent moisture absorption and swelling of the bamboo rod. The rod may have a helical wrapping of wire to further prevent swelling.

U.S Naval Civil Engineering Laboratory in 1966 reported a study providing a set of instructions on how to design and properly construct using bamboo as reinforcement in concrete members. This study recommends 3/4inch (19mm) wide bamboo splits to use as reinforcement and apply waterproof coating to reduce swelling when in contact with concrete. The type of coating depends on the materials available. A brush coat or dip coat of asphalt emulsion is preferable. Native latex, coal tar, paint, dilute varnish, and water-glass (sodium silicate) are other suitable coatings. In any case, only a thin coating should be applied; a thick coating will lubricate the surface and weaken the bond with the concrete.

2.7.3.Design Consideration and Application

a) Bond and Anchorage

The length of embedement necessary to provide an adequate factor of safety against pullout failure is anchorage length.Reinforcement bars are anchored in concrete either by bond stress or hook and bond stress.

b) Lapped Splices

When the available length of bamboo is less than provided length,extend reinforcement bars by lap splices.in lapped splices ,the force in one bar iss transfeered to the surrounding concrete which in turn transfers the force to the adjacent bars.According to the united state Naval Civil Engineering report(1966) splicing reinforcement in any member should be overlapped at least 63.5cm.Splices should never occurs in highly stressed sreas and in no case should more than 30% of the reinforcement be spliced in any one location.(Brink F.E.,1966)

iii. Concrete cover and spacing of reinforcement

Appropriate thickness of concrete cover is essential to ensure adequate fire resistance,sate transmission of bond forces and protection against corrosion or decay.Our code EBCS-2 recommends minimum concrete cover at least equal to the diameter of the bar for steel reinforcement.

3. EXPERIMENTAL PROGRAMS

3.1 Introduction

The experimental program of this research is designed to obtain the flexural tests of steel bamboo reinforced concrete beams and RC beams. The tensile and compressive tests of bamboo were conducted to determine the ultimate tensile and compression strength; which are the most basic type of mechanical properties. The flexural strength tests were conducted by varying the place and percentage of bamboo as top and bottom reinforcement. Moreover, the theoretical ultimate load capacity of the section was determined. In the preparation of samples and conducting tests the guideline in IS, ISO and ASTM standards were followed. In this chapter, the general sample preparations and the experimental set up to accomplish the test are discussed.

3.2. Material Properties

3.2.1. Bamboo

The physical and mechanical properties of bamboo were determined according to IS 6874. Bamboo is an orthotropic material; it has particular mechanical properties in the three mutual directions (longitudinal, radial and tangential). This study was carried out to investigate the tensile and compression strength of bamboo mainly in the longitudinal direction. In addition, the bottom and middle culm parts were taken for test due to its high strength. For this research test samples were taken from Dila which is Y.Alpina species according to Seyoum Kelemwork (Dr) study on Ethiopian Bamboo (2008).

3.2.1.1 Tensile Test

The tensile tests were made for a strip of bamboo parallel to the fibers at bottom and middle position of a culm; hence the tensile strength of bamboo increases from top to bottom part of the culm.

a. Specimen Preparation

The test specimens for tensile strength test were prepared according to IS 6874 & ISO 22157-1, 2**.** According to the report of ISO 22157, the difference in tensile strength between specimens with node and without node is tremendous. Therefore, Six sticks were prepared with node and without node for the tests. The end part of the specimens was laminated with steel plate in order to avoid grip failure during tensile testing.

Figure 3.1 Specimens for Tensile Strength

b. Test setup

Tensile tests were conducted on Universal Testing Machine with model 70-C0807/C. According to ISO 22157-1, the load should be applied continuously throughout the test at a rate of motion of the movable cross head of 0.01mm/s.

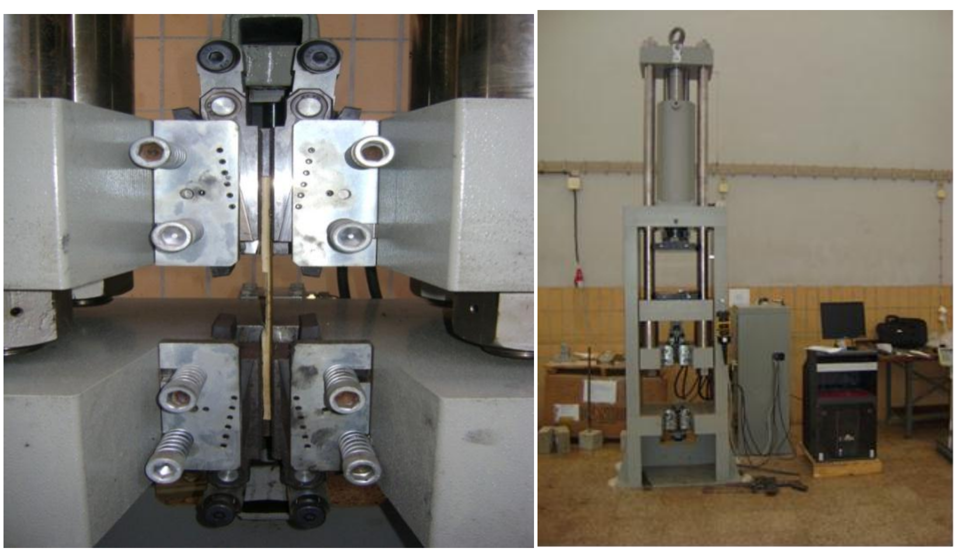


Figure 3.2 Universal Testing Machine

Six specimens with a length of 60mm, width (15-20mm) and thickness (6-11mm) were prepared and tested for tensile strength.

3.2.1.2 Compressive Test

The compressive tests were made for a segment of bamboo culm parallel to the fibers for bottom and middle position of a Culm according to IS 6874.

a) Specimen Preparation

According to IS6874 recommendation, the length of the test sample was equal to the outer diameter for bamboo which have less than 20mm diameter and twice the outer diameter for bamboo which have greater than 20mm outer diameter.

Figure 3.3 Bamboo specimens for compression test

b) Test Setup

Compressive tests of bamboo were conducted on Automatic Compression testing machines with model 50-C36V. Procedure outlined on ISO 22157-1 was used in performing testing. The load was applied at an average rate of 0.01mm/sec or ($1N/mm^2/s$).

Six specimens were prepared for the compressive test of bamboo with diameter (50-60mm), length (100-120mm) and thickness (11.3-16.3mm).

3.2.1.3 Bond Strength of Bamboo

The band strength of bamboo is enhanced by using melted bitumen and applying it to the bamboo strips uniformly with a brush to form thin coats while still hot, the bamboo is covered with coarse sand for 24hours. The bitumen has proved an effective moisture barrier and the sand makes rough surface thus improved the bond strength and there was no pulling out of bamboo sticks from the beam specimen during flexural test.

Figure 3.4 Threated bamboo sticks

3.2.2 Concrete

ACI mix design method used for normal steel reinforced concrete is applied in the preparation of mix design for bamboo reinforced concrete specimens [8].Concrete slump was made as low as workability will allow minimizing excess water which causes swelling of the bamboo.

From sieve analysis 3.0 fineness modules of sand was obtained and maximum size of 20mm aggregate is used. In order to obtain a 28 day concrete compressive strength 25Mpa the following quantity of material is adopted.

Table3.1 Quantity of materials

Quantity of Material for C-25(kg/m^3)				
material	Water	Cement	Fine aggregate	coarse aggregate
Quantity	197.4	448.6	752.71	1064.65

The slump was the difference in height of the mold so that the displacement of the cone was measured to the highest point. From the tests a slump of 27 mm was recorded. The concrete mix was kept identical for all flexural test samples and the concrete was allowed to set for a period of 28 days to obtain the 28 days concrete strength and an average concrete compressive strength of 24.8Mpa is recorded.

3.2.3 Reinforcement

The reinforcement used on the beam specimens is checked against corrosion and rust. The tensile strength of steel used in the specimen beam is 300Mpa.

Figure 3.5 Fresh concrete mix and reinforcement

3.3. Flexural Test

3.5.1. Beam Specimen Preparation

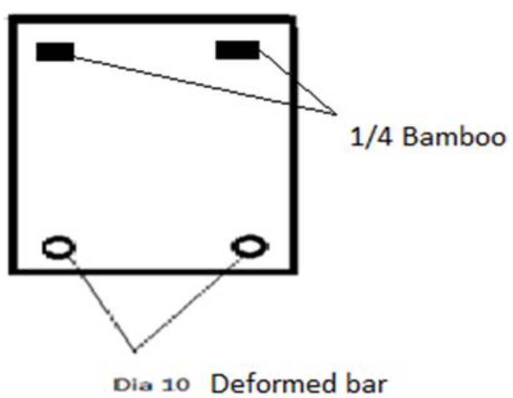
In the preparation of test specimen beams, procedure outlined in ASTM standard and U.S Naval Civil Engineering Laboratory was followed. Considering the laboratory conditions and the sizes of bamboo strips a beam length of 1000mm was preferred. According to ASTM standard, which recommend a ratio of length to depth greater than 4, a cross sectional area of 15cmX20cm was used. To be acquainted with the behavior of bamboo & steel in concrete beams different positions of bamboo & steel arrangement was followed .The specimens were designed to resist 50KN load for all conditions of the beam material property detail is shown in the Table3.4 &3.5.

a. Control Beams

Two Reinforced concrete beams were prepared with length 1000mm, width 150mm and height 200mm as a control beam with single reinforcement and double reinforcement. For singly reinforced beam, two diameter 10 deformed bars are used on the tensile zone and for doubly reinforced beam two diameter 10 and two diameter 8 deformed bars on the tensile and compression zone, respectively, are used.

b. Composite Beams

Two bamboo steel reinforced concrete beams with 1000mm, width 150mm and height 200mm are prepared with different percentage of bamboo and steel in compression and tension zone. On the first beam, bamboo is placed in the compression zone as a substitute for nominal reinforcement which is used to support the stirrups as shown in the Figure 3.6a. On the second beam bamboo is used in the tension zone with steel as shown in the Figure 3.6b.



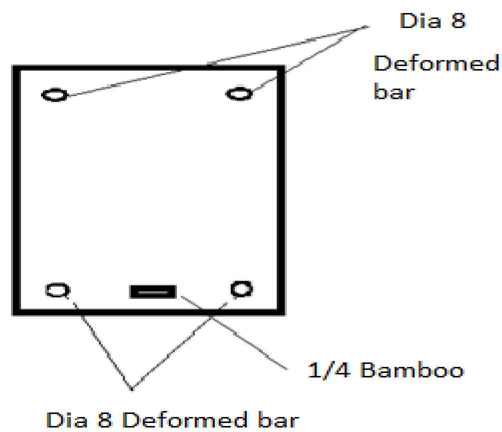


Figure 3.6a Partial Bamboo Rebar

Figure 3.6b partial bamboo rebar

c. Bamboo Reinforced Beam

A bamboo reinforced beam specimen is prepared to see if full replacement of reinforcement is possible. The beam is composed of four bamboos ¼ culm from bottom and middle part with a length of 1000mm,width 150mm and height 200mm.

Table 3.2 RC Beam Specimens

Design of steel reinforced concrete beam		
Type of Beam	Beam-1	Beam-2
Size of beam	150*200	150*200
Grade of concrete	C-25	C-25
Grade of steel	F-300	F-300
Reinforcement Provided	bottom2ø10	bottom2ø10 ,2ø8 top
stirrups	ø 8 c/c 100mm	ø 8 c/c 100mm
Cover	25	25

Table 3.3 Composite and Bamboo reinforce

Design of steel Bamboo reinforced concrete beam			
Type of Beam	**Beam-3**	**Beam-4**	**Beam-5**
Size of beam	150*200	150*200	150*200
Grade of concrete	C-25	C-25	C-25
Grade of steel	F-300	F-300	F-300
Type of other Reinforcement	two 1/4 bamboo	one 1/4 bamboo	Bamboo
Reinforcement provided	2ø10	4ø8(top&bottom)	4(top&bottom)
stirrups	ø 8 c/c 100mm	ø 8 c/c 100mm	ø 8 c/c 100mm
Cover	25	25	25

3.5.2. Test Setup

Flexural tests were conducted on Universal Testing Machine with model 70-C0807/C. The test was conducted with one point loading. Test procedure listed on ASTM C 78-02 was used to perform flexural test. The loading was applied at a distance of 500mm at the center of the beam specimen and the support was indented 100mm from left and right side of the beam as shown in the figure 3.7 below.

Figure 3.7 Beam set up on universal Testing Machine

4. Experimental and Theoretical Results

4.1. Introduction

This chapter presents the results of the tensile and compressive strength of bamboo specimens compressive strength of concrete, one point flexural tests performed on six specimens which were Grouped in to three category; Reinforced concrete beam specimens ,steel bamboo reinforced concrete beam specimens and Bamboo reinforced beam specimen. The result of experiment is compared with the theoretical failure load of the beam specimens.

4.2. Bamboo Test Results

a) Tensile strength Test

Tensile tests were conducted on specimens with nodes. Nodes are weak and brittle in resistance to tensile force as referred in ISO-22157.From the test results of six specimens an average tensile strength 119.9 Mpa obtained from four specimens with a standard deviation of 8.6 as shown in the Table 4.1 below.

Table 4.1 Tensile strength Test Result of Bamboo

Specimen Code	Specimen Size(mm)			Cross sectional Area(mm2)	Failure Load(KN)	Stress(Mpa)
	L	W	T			
TB1	59.9	19.8	7.1	140.58	17.6	125.2
TB2	60	16	8.3	132.8	15.7	118.2
TB3	60	18	6.5	117	14.9	127.4
TB4	59.9	20	6.8	136	14.8	108.8

Figure 4.2 Bamboo specimens after testing

Figure 4.1 Bamboo sticks after test

In the experimental test failures in most of the specimens occurred at the node. A few numbers of test specimens failed by splitting in to two parts and then followed by node failure as shown in the Figure 4.2, above and others show a combination of splitting, shear and node failure.

b) Compressive strength Test

Compression tests were conducted on specimens with nodes and without nodes for eight tests specimens. From the test the ultimate compression resistance of the Node splitting type failure, Splitting Failure, Node failure specified specie was recorded. Brooming or end-rolling type of failure was observed in most of the test specimen. The entire three specimens with node failed with the end rolling type of failures. This type of failure is usually associated with excess moisture at the ends of the specimen or improper cutting of the specimen which is usually associated with a reduced load. The other type of failures which were observed in most of the specimens were splitting and shearing. Most samples failed by dividing in to two parts which is a splitting type of failure.

Table 4.2 Compressive Strength Test of Bamboo

Specimen Code	Specimen Size(mm)			Cross sectional Area(mm2)	Failure Load(KN)	Stress(Mpa)
	D	L	T			
CB1	50	100	13.3	1533.44	67.2	61.1
CB2	52.3	104.6	16.1	1830	85.6	46.8
CB3	60	120	14.4	2066.5	81.8	39.6
CB4	58.1	116.2	16.3	1838.36	93.7	36.6

Table 4.3 Experimental and Theoretical Failure Load

The general compression test results are summarized in the Table 4.2, shown above the mean value of the sample specimen result of compressive strength is 46Mpa with a standard deviation of 10.6 as shown in the table above.

4.3. Concrete Test Results

Concrete is a composite material consisting of cement, gravel, sand and water. After hardening of this composite material the material can be regarded as a mortar mix including distributed aggregates. Concrete showed a very brittle behavior after reaching its ultimate load. Generally the concrete workability is measured with a slump test which was recorded as 27mm for the mix design and the average concrete compressive strength obtained to be 24.8Mpa after curing for 28 days.

Figure 4.3 Compressive strength test

4.4. Flexural Test of Beam Specimen

From the experimental test the load deflection graph, ultimate carrying capacity and the type of failure were recorded. The deflection at first crack was recorded from the load and deflection curve which was found at the point where the stiffness of the beam changed. In addition the maximum deflection was read from this curve. Generally bond, pure flexural and a combination of shear and flexure types of failures were observed. The flexure and shear combination failure were the most dominating occurrence as shown in Figure 5.1. Summary of flexural test results of beam specimens is shown in Table 4.3. The load displacement diagrams of the test beam specimens are shown in chart 5.1. Moreover, the experimental failure load of test specimens and the calculated theoretical failure load are shown in chart 5.2.

Table 4.3 Experimental and Theoretical Failure Load

Type of Beam	Beam -1	Beam-2	Beam-3	Beam-4	Beam-5
Total Reinforcement	2Ø10	2Ø10 &2Ø8	2Ø10&1/4 bamboo culm	4Ø8& 1/4 bamboo	1/4 four bamboo
Reinforcement Area Tension Zone(mm^2)	157	157	157	234.5	268
Reinforcement Area Compression Zone(mm^2)	0	100.5	268	100.5	268
Experimental Failure Load(KN)P'	50.1	73.4	58.8	65.5	30.1
Theoretical Ultimate Load(KN)Pu	49	72.8	65.8	67.3	59.8
Pu/P'	0.98	0.99	1.12	1.03	1.99

5. ANALYSES AND DISCUSSION

5.1. Observation Made

The flexural failure mode was observed for all types of beam specimens as shown in figure 5.1.The yielding of steel, bamboo took place and this was followed by crushing of concrete in the compression zone. Since all the beams were designed as under-reinforced, the failure started by yielding of the tension steel bar before the compression failure of concrete as expected.Also,the stirrup spacing was kept at 100mm center in the shear zone and thus all beams failed in typical flexural mode. For all types of beam specimens, failure started with flexural crack and extended up to the neutral axis. The first flexural crack, after reaching the neutral axis, started to incline to from compression failure zone and the crushing of concrete took place in the zone during failure.

Figure 5.1 Failure Mode of Beam-3

5.1.1. Failure modes and failure mechanism

For the tested beams, the materials were in elastic stage at the beginning of the test. And with the increasing of load, the beams showed some plastic behaviors and the flexural stiffness decreased. Also the deflection of the beams was obvious. Then micro-cracks appeared at some defects (knots, grain slope and finger joints, etc.) in the tension area, and low voice sent out at the same time.

Finally when the beam collapsed, the beam deflection was quite big. Moreover, once failure began at the outmost bamboo culm in the tension area, failure progressed very quickly because of the subsequent longitudinal splitting as the bamboo failed in tension across the grain. Besides of Beam 3, which failed due to de bonding of bamboo and concrete, failure modes were mostly vertical and inclined flexural failure mode.

Shear failure was not a consideration for all beams since stirrup spacing adopted was 100mm, which is less than the maximum allowable spacing.

5.2. Load-Deflection Behavior

a) The load deflection behavior of RC beams with simply supported system is generally the same; when the concrete cracks, moment of inertia of the beam decrease which leads to low stiffness of the beam. This cause yielding of steel after this point there is large deflection with small increment of load and results with parabolic load deflection graph. The chart below ends at the maximum load carrying capacity of the beams and goes to zero after making parabolic down ward curve but for simplicity purpose the chart didn't continue after failure load.

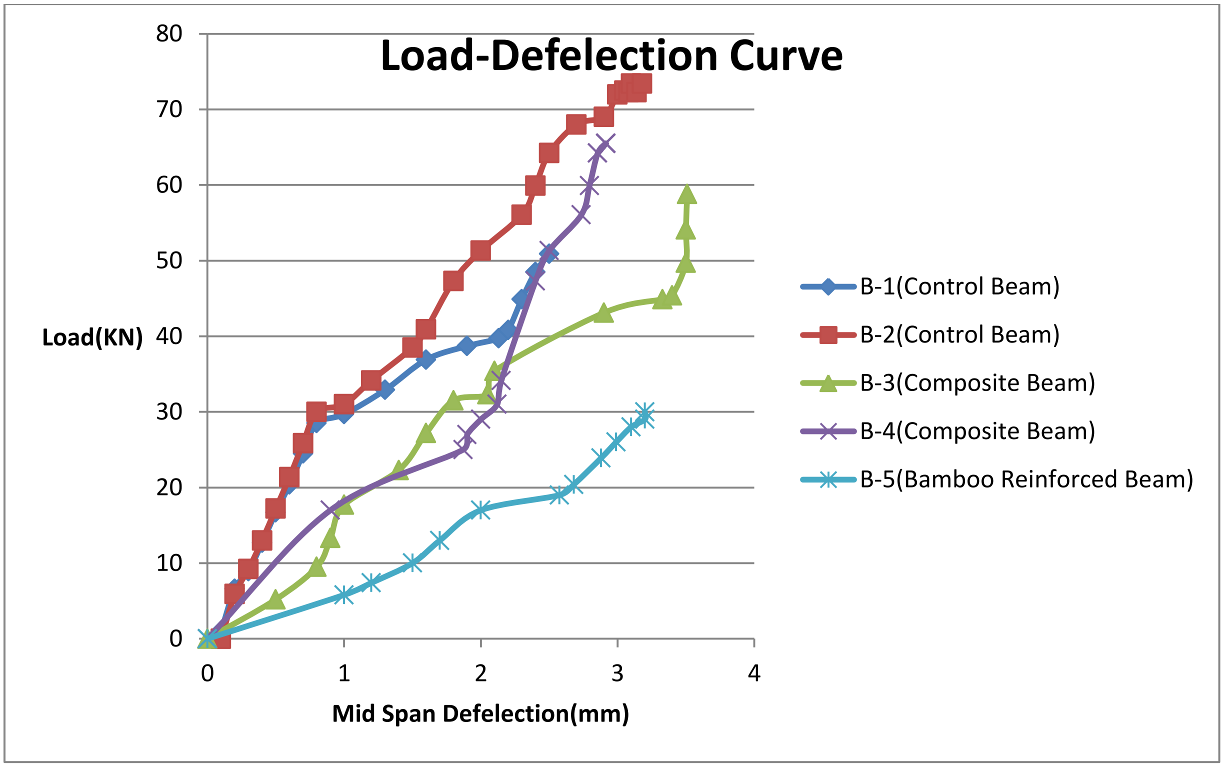


Chart 5.1.The load displacement curve

For bamboo reinforced concrete beams the deflections significantly increases with increasing load until the appearance of first crack in the concret.immidiately after, the deflection increased significantly due to local bond slippage and due to the nature of bamboo which is a brittle material.

The other behavior in the load deflection diagram is that there is a fluctuation of resistance especially around the maximum carrying capacity. This behavior was more happen in the steel bamboo beam specimens. This fluctuation of resistance is believed that due to the bondage effect of bamboo. During initial loading the bond resistance is by adhesion and friction. As loading progress slip of bamboo will be occurred and the bond resistance by adhesion and friction would be lost. At this time the bond resistance would be transfer by nodes which act as bearing action, then the bondage increase and at the same time the resistance would be increased. Since there are an average of three nodes in one split of bamboo and there are a number of splits this action might happened for a number of times as it is seen in the diagram.

5.3. Ultimate Load Capacity

The theoretical ultimate moments were calculated using the ultimate strength of the reinforcement, while that of bamboo were calculated using the ultimate strength of bamboo without a material factor of safety for all cases. Chart 5.2 shows the load carrying capacity of Beam-1, Beam-2, Beam-3, Beam-4 and Beam-5 tested under center point loading.

Case-1

The control beam specimen is designed to resist 50KN load reinforced only in the tensile zone but most of the the time nominal reinforcement at the top is provided for stirrup tying.therefore,in this study the nominal reinforcement is replaced by ¼ two bamboo culms and its load carrying capacity was investigated in the laboratory. The result showed that bamboo reinforced concrete had 8.7% more load carrying capacity than singly reinforced beam, in addition to tying purpose.

Case-2

The reference RC beam is designed to resist a load of 55KN as a double reinforcement beam with two diameters 10 and diameter 8 deformed bars as a bottom and top respectively. The reinforcements in the compression zone were replaced by two ¼ bamboo culms each with an average area of 134mm2.The result showed bamboo reinforced concrete beam specimen can carry 105% of the design load and 78.3% of the respective double reinforcement concrete beam with steel.

On the other beam,35.9% of the tension reinforcement area was replacement by 85% of bamboo reinforcement and the compression reinforcement kept the same. The load carrying capacity of steel bamboo reinforced concrete beam (beam-4) was 10.% below from the reference beam(beam-2) but still can withstand the design load with 119%.

Case -3

The control beam is designed to resist a load of 65KN as a doubly reinforced beam with diameter 10 and diameter 8 deformed bar at the bottom and top respectively. From the reinforcement area at the tension zone 36% was replaced by bamboo with an average area of 134mm2 and compression zone reinforcement remained the same. This arrangement of reinforcement and bamboo carried the design load around 100%.

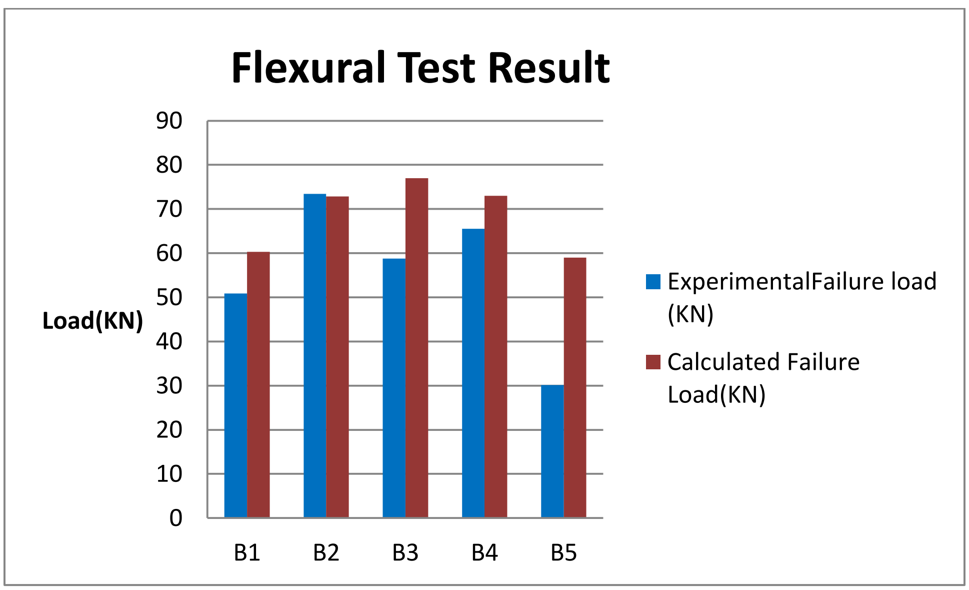


Chart 5.2.Theoretical & Experimental Load

The ultimate load capacity on Beam-5 showed a great difference between the experimental and theoretical value due to the following reasons.

Theoretical value was calculated based on RC design procedure the only difference was material property and perfect bond between bamboo and concrete was assumed.

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

Summarized below are the results of the study:

- Bamboo can be used as reinforcement in nominal reinforcement places for singly reinforced beam.
- when using bamboo as a reinforcement higher factor of safety should be considered
- The experimental results showed that replacing bamboo in place of steel requires large area of bamboo.
- Considering the ultimate load capacity as a measurement ; bamboo reinforced sections have less load carrying capacity when used as a main reinforcement on doubly reinforced beam , compared with RC beams but still can with stand the design load.

6.2. Recommendations

This study initiate use of bamboo as reinforcement complement to previous studies but would like the following by study in details for prompt use in the construction industry.

- Development of factor of safety to calculate the allowable stress of bamboo for use in design calculation on basis of statically data.
- Experimental study should be carried on different percentage of bamboo reinforced concrete columns to investigated bond strength, buckling behavior, carrying capacity and type of failures
- Long term studies on the durability, fatigue of bamboo reinforced concrete beam and Thermal effect of bamboo by conducting pullout tests on different gradient of temperature.
- Experiment with other types of coating and compared the bonding strength with the traditional asphalt emulsion coatings
- To understand a more in depth correlation between the properties of bamboo and its structure, determine a method for measuring the size and counting the number of fibers Throughout culm.

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